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Muon anomalous magnetic moment and positron excess at AMS-02 in a gauged horizontal symmetric model

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Abstract: We studied an extension of the standard model with a fourth generation of fermions to explain the discrepancy in the muon $(g-2)$ and explain the positron excess seen in the AMS-02 experiment. We introduce a gauged $\mathrm{SU}(2)_{\mathrm{HV}}$ horizontal symmetry between the muon and the 4th generation lepton families. The 4th generation right-handed neutrino is identified as the dark matter with mass $\sim 700\,\mathrm{GeV}$. The dark matter annihilates only to $(\mu^+\mu^-)$ and $(\nu_\mu^c\,\nu_\mu)$ states via $\mathrm{SU}(2)_{\mathrm{HV}}$ gauge boson. The $\mathrm{SU}(2)_{\mathrm{HV}}$ gauge boson with mass $\sim 1.4\,\mathrm{TeV}$ gives an adequate contribution to the $(g-2)$ of muon and fulfill the experimental constraint from BNL measurement. The higgs production constraints from 4th generation fermions is evaded by extending the higgs sector.

Keywords: Beyond Standard Model, Cosmology of Theories beyond the SM

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Contents

1 Introduction

There exist two interesting experimental signals namely the muon $(g-2)$, measured at BNL [1, 2] and the excess of positrons measured by AMS-02 [20, 21], which may have a common beyond standard model (SM) explanation.

There is a discrepancy at 3.6σ level between the experimental measurement [1, 2] and the SM prediction [3–9] of muon anomalous magnetic moment,

$$\Delta a_\mu \equiv a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (28.7 \pm 8.0) \times 10^{-10} \tag{1.1}$$

where a_μ is the anomalous magnetic moment in the unit of $e/2m_\mu$. In the standard model, contribution of W boson to the muon anomalous magnetic magnetic moment goes as $a_\mu^W \propto m_\mu^2/M_W^2$ and we have $a_\mu^{\rm SM} = 19.48 \times 10^{-10}$ [10].

In minimal supersymmetric standard model (MSSM) [11, 12], we get contributions to muon $(g-2)$ from neutralino-smuon and chargino-sneutrino loops. In all MSSM diagrams there still exist a m_μ suppression in $(g-2)$, arising from the following cases: (a) in case of bino in the loop, the mixing between the left and right handed smuons is $\propto m_\mu$ (b) in case of wino-higgsino or bino-higgsino in the loop, the higgsino coupling with smuon is $\propto y_\mu$, so there is a m_μ suppression (c) in the case of chargino-sneutrino in the loop, the higgsino-muon coupling is $\propto y_\mu$, which again gives rise to m_μ suppression. Therefor in MSSM $a_\mu^{\rm MSSM} \propto m_\mu^2/M_{\rm SUSY}^2$, where $M_{\rm SUSY}$ is proportional to the mass of the SUSY particle in the loop.

One can evade the muon mass suppression in $(g-2)$ with a horizontal gauge symmetry. In [13] a horizontal $U(1)_{L_\mu - L_\tau}$ symmetry was used in which muon $(g-2)$ is proportional to m_τ and $a_\mu \propto m_\mu m_\tau / m_{Z'}^2$, where $L_\mu - L_\tau$ gauge boson mass $m_{Z'} \propto 100\,\mathrm{GeV}$ gives the required a_μ. A model independent analysis of the beyond SM particles which can give a contribution to a_μ is studied in [14]. The SM extension needed to explain muon $(g-2)$ has also been related to dark matter [15, 16] and the implication of this new physics in LHC searches has been studied [17]. An explanation of $(g-2)$ from the 4th generation leptons has also been given in [18, 19].

The second experimental signal, which we address in this paper is the excess of positron over cosmic-ray background, which has been observed by AMS-02 experiment [20] upto energy $\sim 425\,\text{GeV}$ [21]. An analysis of AMS-02 data suggests that a dark matter (DM) annihilation interpretation would imply that the annihilation final states are either μ or τ [23, 24]. The dark matter annihilation into $e^{\pm}$ pairs would give a peak in positron signal, which is not seen in the positron spectrum. The branching ratio of τ decay to e is only 17% compared to μ, which makes μ as the preferred source as origin of high energy positrons. The AMS-02 experiment does not observe an excess, beyond the cosmic-ray background, in the antiproton flux [25, 26], indicating a leptophilic dark matter [27, 28, 33].

In this paper, we introduce a 4th generation of fermions and a $SU(2)_{HV}$ vector gauge symmetry between the 4th generation leptons and the muon families. In our model, the muon $(g-2)$ has a contribution from the 4th generation charged lepton μ', and the $SU(2)_{HV}$ gauge boson θ^+,

$$\Delta a_\mu \propto \frac{m_\mu m_{\mu'}}{M_{\theta^+}^2} \tag{1.2}$$

and from the neutral higgs scalars (h, A),

$$\Delta a_\mu \propto \frac{m_\mu}{m_{\mu'}} \tag{1.3}$$

and from the charged higgs $H^{\pm}$ the contribution is,

$$\Delta a_\mu \propto -\frac{m_\mu m_{\nu_{\mu'}}}{m_{H^\pm}^2} \tag{1.4}$$

In all these cases, there is no quadratic suppression $\propto m_\mu^2$ because of the horizontal symmetry. By choosing parameters of the model without any fine tunning, we can obtain the required number $\Delta a_\mu = 2.87 \times 10^{-9}$ within 1σ.

In this model, the 4th generation right-handed neutrino $\nu_{\mu' R}$, is identified as dark matter. The dark matter annihilates to the standard model particles through the $SU(2)_{HV}$ gauge boson θ_3 and with the only final states being $(\mu^+\mu^-)$ and $(\nu_\mu^c\, \nu_\mu)$. The stability of DM is maintained by taking the 4th generation charged lepton to be heavier than DM. To explain the AMS-02 signal [20, 21], one needs a cross-section (CS), $\sigma v_{\chi\chi\to\mu^+\mu^-} = 2.33 \times 10^{-25}\,\text{cm}^3/\text{sec}$, which is larger than the CS, $\sigma v_{\chi\chi\to SM} \sim 3 \times 10^{-26}\,\text{cm}^3/\text{sec}$, required to get the correct thermal relic density $\Omega h^2 = 0.1199 \pm 0.0027$ [29, 30]. In our model, the enhancement of annihilation CS of DM in the galaxy is achieved by the resonant enhancement mechanism [31–33], which we attain by taking $M_{\theta_3} \simeq 2m_\chi$.

This paper is organized as follows: in section 2, we describe the model. In section 3 we discuss the dark matter phenomenology and in section 4, we compute the $(g-2)$ contributions from this model and then give our conclusion in section 5.

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Particles	$G_{\rm STD} \times \mathrm{SU}(2)_{\rm HV}$ quantum numbers
$\psi_{eLi} \equiv (\nu_e, e)$	$(1, 2, -1, 1)$
$\Psi_{Li\alpha} \equiv (\psi_\mu, \psi_{\mu'})$	$(1, 2, -1, 2)$
$\psi_{\tau Li} \equiv (\nu_\tau, \tau)$	$(1, 2, -1, 1)$
$E_{R\alpha} \equiv (\mu_R, \mu'_R)$	$(1, 1, -2, 2)$
$N_{R\alpha} \equiv (\nu_{\mu R}, \nu_{\mu' R})$	$(1, 1, 0, 2)$
e_R, τ_R	$(1, 1, -2, 1)$
$\nu_{eR}, \nu_{\tau R}$	$(1, 1, 0, 1)$
ϕ_i	$(1, 2, 1, 1)$
$\eta^\beta_{i\alpha}$	$(1, 2, 1, 3)$
χ_α	$(1, 1, 0, 2)$

Table 1. Representation of the various fields in the model under the gauge group $G_{\rm STD} \times \mathrm{SU}(2)_{\rm HV}$.

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2 Model

In addition to the three generations of quarks and leptons, we introduce the 4th generation of quarks (c', s') and leptons (ν'_μ, μ') (of both chiralities) in the standard model. We also add three right-handed neutrinos and extend the gauge group of SM by horizontal symmetry denoted by $\mathrm{SU}(2)_{\rm HV}$, between the 4th generation lepton and muon families. Addition of three right-handed neutrinos ensures that the model is free from SU(2) Witten anomaly [34]. We assume that the quarks of all four generations and the leptons of e and τ families are singlet of $\mathrm{SU}(2)_{\rm HV}$ to evade the constraints from flavour changing processes. The $\mathrm{SU}(2)_{\rm HV}$ symmetry can be extended to e and τ families by choosing suitable discrete symmetries, however in this paper we have taken e and τ families to be singlet of $\mathrm{SU}(2)_{\rm HV}$ for simplicity and discuss the most economical model, which can explain muon $(g-2)$ and AMS-02 positron excess at the same time.

We denote the left-handed muon and 4th generation lepton families by $\Psi_{Li\alpha}$ and their right-handed charged and neutral counterparts by $E_{R\alpha}$ and $N_{R\alpha}$ respectively (here i and α are the $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_{\rm HV}$ indices respectively and run through the values 1 and 2). The left-handed electron and tau doublets are denoted by ψ_{eLi} and $\psi_{\tau Li}$ and their right-handed counterparts by e_R and τ_R respectively. The gauge fields of $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{SU}(2)_{\rm HV}$ groups are denoted by A^a_μ, B_μ and θ^a_μ $(a = 1, 2, 3)$ with gauge couplings g, g' and g_H respectively.

The leptons transformations under the gauge group, $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{SU}(2)_{\rm HV} \equiv G_{\rm STD} \times \mathrm{SU}(2)_{\rm HV}$ are shown in table 1. From the assigned quantum numbers, it is clear that the $\mathrm{SU}(2)_{\rm HV}$ gauge bosons connect only the leptons pairs, $\psi_{\mu_L} \leftrightarrow \psi_{\mu'_L}$ and $(\mu_R, \nu_{\mu R}) \leftrightarrow (\mu'_R, \nu'_{\mu R})$. This assignment prevents the flavour changing process like $\mu \to e\gamma$ for which there are stringent bounds, and also ensures the contribution of heavy lepton μ' to the muon $(g-2)$ as shown in figure 4. In our $G_{\rm STD} \times \mathrm{SU}(2)_{\rm HV}$ model, the gauge couplings of the muon and 4th generation lepton families are,

$$\mathcal{L}_\psi = i\bar{\Psi}_{Li\alpha}\gamma^\mu\left(\partial_\mu - \frac{i}{2}g\tau\cdot A_\mu + ig'B_\mu - \frac{i}{2}g_H\tau\cdot\theta_\mu\right)_{ij;\alpha\beta}\Psi_{Lj\beta} \\ + i\bar{E}_{R\alpha}\gamma^\mu\left(\partial_\mu + i2g'B_\mu - \frac{i}{2}g_H\tau\cdot\theta_\mu\right)_{\alpha\beta}E_{R\beta} + i\bar{N}_{R\alpha}\gamma^\mu\left(\partial_\mu - \frac{i}{2}g_H\tau\cdot\theta_\mu\right)_{\alpha\beta}N_{R\beta} \tag{2.1}$$

The "neutral-current" of $\mathrm{SU(2)_{HV}}$ contributes to the annihilation process, $(\nu_{\mu'}\nu_{\mu'}) \to \theta_3^* \to (\mu^+\mu^-), (\nu_\mu^c\ \nu_\mu)$, which is relevant for the AMS-02 and relic density calculations. The "charge-changing" vertex $\mu\mu'\theta^+$, contributes to the $(g-2)$ of the muon.

To evade the bounds on the 4th generation from the higgs production at LHC, we extend the higgs sector (in addition to ϕ_i) by a scalar $\eta_{i\alpha}^\beta$, which is a doublet under SU(2) and triplet under $\mathrm{SU(2)_{HV}}$. As a SU(2) doublet $\eta_{i\alpha}^\beta$ evades 4th generation bounds from the overproduction of higgs in the same way as [35, 36], in that the 125 GeV mass eigenstate is predominantly η which has no Yukawa couplings with the quarks. As $\eta_{i\alpha}^\beta$ is a triplet under $\mathrm{SU(2)_{HV}}$, its Yukawa couplings with the muon and 4th generation lepton families split the masses of the muon and 4th generation leptons. We also introduce a $\mathrm{SU(2)_{HV}}$ doublet χ_α, which generates masses for $\mathrm{SU(2)_{HV}}$ gauge bosons. The quantum numbers of the scalars are shown in table 1. The general potential of this set of scalars $(\phi_i, \eta_{i\alpha}^\beta, \chi_\alpha)$ is given in [37]. Following [37], we take the vacuum expectation values (vevs) of scalars as,

$$\begin{aligned} \langle\phi_i\rangle &= \langle\phi\rangle\delta_{i2} \\ \langle\eta_{i\alpha}^\beta\rangle &= \langle\eta\rangle\delta_{i2}(\delta_{\alpha1}\delta^{\beta1} - \delta_{\alpha2}\delta^{\beta2}) \\ |\langle\chi\rangle|^2 &= |\langle\chi_1\rangle|^2 + |\langle\chi_2\rangle|^2 \end{aligned} \tag{2.2}$$

where $\langle\phi_i\rangle$ breaks $\mathrm{SU(2)}_L$, $\langle\chi_\alpha\rangle$ breaks $\mathrm{SU(2)_{HV}}$ and $\langle\eta_{i\alpha}^\beta\rangle$ breaks both $\mathrm{SU(2)}_L$ and $\mathrm{SU(2)_{HV}}$ and generate the TeV scale masses for $\mathrm{SU(2)_{HV}}$ gauge bosons. The mass eigenstates of the scalars will be a linear combination of $\phi_i, \eta_{i\alpha}^\beta$ and χ_α. We shall assume that the lowest mass eigenstate h_1 with the mass ~ 125 GeV is primarily constituted by $\eta_{i\alpha}^\beta$. We shall also assume that the parameters of the higgs potential [37] are tuned such that mixing between h_1 and ϕ_i is small,

$$\langle h_1|\phi_i\rangle \simeq 10^{-2} \tag{2.3}$$

The Yukawa couplings of 4th generation quarks are only with ϕ_i, therefore the 125 GeV Higgs will have very small contribution from the 4th generation quarks loop.

The gauge couplings of the scalar fields $\phi_i, \eta_{i\alpha}^\beta$ and χ_α are given by the Lagrangian,

$$\mathcal{L}_s = |\left(\partial_\mu - \frac{i}{2}g\tau\cdot A_\mu - ig'B_\mu\right)\phi|^2 + |\left(\partial_\mu - \frac{i}{2}g\tau\cdot A_\mu - ig'B_\mu - ig_HT\cdot\theta_\mu\right)\eta|^2 \\ + |\left(\partial_\mu - \frac{i}{2}g_H\tau\cdot\theta\right)\chi|^2 \tag{2.4}$$

where $\tau_a/2$ $(a = 1,2,3)$ are 2×2 matrix representation for the generators of SU(2) and T_a $(a = 1,2,3)$ are 3×3 matrix representation for the generators of SU(2). After expanding

$\mathcal{L}_s$ around the vevs defined in eq. (2.2), the masses of gauge bosons come,

$$M_W^2 = \frac{g^2}{2}(2\langle\eta\rangle^2 + \langle\phi\rangle^2)\,, \qquad M_Z^2 = \frac{g^2}{2}\sec^2\theta_W(2\langle\eta\rangle^2 + \langle\phi\rangle^2)\,, \qquad M_A^2 = 0\,,$$
$$M_{\theta^+}^2 = g_H^2\left(4\langle\eta\rangle^2 + \frac{1}{2}\langle\chi\rangle^2\right), \qquad M_{\theta_3}^2 = \frac{1}{2}g_H^2\langle\chi\rangle^2 \tag{2.5}$$

we tune the parameters in the potential such that the vevs of scalars are,

$$\begin{aligned} 2\langle\eta\rangle^2 + \langle\phi\rangle^2 &= (174\,\mathrm{GeV})^2 \\ \langle\chi\rangle &= 22.7\,\mathrm{TeV} \end{aligned} \tag{2.6}$$

for the generation of large masses for 4th generation leptons μ', $\nu_{\mu'}$ and $\mathrm{SU(2)_{HV}}$ gauge bosons θ^+, θ_3. The Yukawa couplings of the leptons are given by,

$$\begin{aligned} \mathcal{L}_Y = & -h_1\bar{\psi}_{eLi}\phi_i e_R - \tilde{h}_1\epsilon_{ij}\bar{\psi}_{eLi}\phi^j\nu_{eR} - h_2\bar{\Psi}_{Li\alpha}\phi_i E_{R\alpha} - \tilde{h}_2\epsilon_{ij}\bar{\Psi}_{Li\alpha}\phi^j N_{R\alpha} - k_2\bar{\Psi}_{Li\alpha}\eta^\beta_{i\alpha}E_{R\beta} \\ & - \tilde{k}_2\epsilon_{ij}\bar{\Psi}_{Li\alpha}\eta^{j\beta}_\alpha N_{R\beta} - h_3\bar{\psi}_{\tau Li}\phi_i\tau_R - \tilde{h}_3\epsilon_{ij}\bar{\psi}_{\tau Li}\phi^j\nu_{\tau R} + \mathrm{h.c.} \end{aligned} \tag{2.7}$$

after corresponding scalars take their vevs as defined in eq. (2.2), we obtain

$$\begin{aligned} \mathcal{L}_Y = & -h_1\bar{\psi}_{eL2}\langle\phi\rangle e_R - \tilde{h}_1\bar{\psi}_{eL1}\langle\phi\rangle\nu_{eR} - \bar{\Psi}_{L2\alpha}[h_2\langle\phi\rangle + k_2\langle\eta\rangle(\delta_{\alpha1} - \delta_{\alpha2})]E_{R\alpha} \\ & - \bar{\Psi}_{L1\alpha}[\tilde{h}_2\langle\phi\rangle + \tilde{k}_2\langle\eta\rangle(\delta_{\alpha1} - \delta_{\alpha2})]N_{R\alpha} - h_3\bar{\psi}_{\tau L2}\langle\phi\rangle\tau_R - \tilde{h}_3\bar{\psi}_{\tau L1}\langle\phi\rangle\nu_{\tau R} \\ & - h_1\bar{\psi}_{eLi}\phi'_i e_R - \tilde{h}_1\epsilon_{ij}\bar{\psi}_{eLi}\phi'^j\nu_{eR} - \bar{\Psi}_{Li\alpha}[h_2\phi'_i\delta^\beta_\alpha + k_2\eta'^\beta_{i\alpha}]E_{R\beta} \\ & - \bar{\Psi}_{Li\alpha}[\tilde{h}_2\epsilon_{ij}\phi'^j\delta^\beta_\alpha + \tilde{k}_2\epsilon_{ij}\eta'^{j\beta}_\alpha]N_{R\beta} - h_3\bar{\psi}_{\tau Li}\phi'_i\tau_R - \tilde{h}_3\epsilon_{ij}\bar{\psi}_{\tau Li}\phi'^j\nu_{\tau R} + \mathrm{h.c.} \end{aligned} \tag{2.8}$$

where ϕ'_i and $\eta'^\beta_{i\alpha}$ are the shifted fields. From eq. (2.8), we see that the muon and 4th generation leptons masses get split and are given by,

$$\begin{aligned} & m_e = h_1\langle\phi\rangle\,, \qquad m_\tau = h_3\langle\phi\rangle\,, \qquad m_{\nu_e} = \tilde{h}_1\langle\phi\rangle\,, \qquad m_{\nu_\tau} = \tilde{h}_3\langle\phi\rangle \\ & m_\mu = h_2\langle\phi\rangle + k_2\langle\eta\rangle\,, \qquad m_{\nu_\mu} = \tilde{h}_2\langle\phi\rangle + \tilde{k}_2\langle\eta\rangle\,, \\ & m_{\mu'} = h_2\langle\phi\rangle - k_2\langle\eta\rangle\,, \qquad m_{\nu_{\mu'}} = \tilde{h}_2\langle\phi\rangle - \tilde{k}_2\langle\eta\rangle \end{aligned} \tag{2.9}$$

Thus by choosing the suitable values of Yukawas, the required leptons masses can be generated.

3 Dark matter phenomenology

In our model, we identify the 4th generation right-handed neutral lepton ($\nu'_{\mu R} \equiv \chi$) as the dark matter, which is used to fit AMS-02 data [20, 21]. The only possible channels for DM annihilation are into ($\mu^+\mu^-$) and ($\nu^c_\mu\ \nu_\mu$) pairs (figure 1). In this scenario for getting the correct relic density, we use the Breit-Wigner resonant enhancement [31–33] and take $M_{\theta_3} \simeq 2m_\chi$. The annihilation CS can be tuned to be $\sim 10^{-26}\,\mathrm{cm^3\,s^{-1}}$ with the resonant enhancement, which gives the observed relic density. In principle the dark matter can decay into the light leptons via $\mathrm{SU(2)_{HV}}$ gauge boson θ^+ and scalar $\eta^\beta_{i\alpha}$, but by taking the mass of 4th generation charged leptons μ' larger than χ, the stability of dark matter can be ensured.

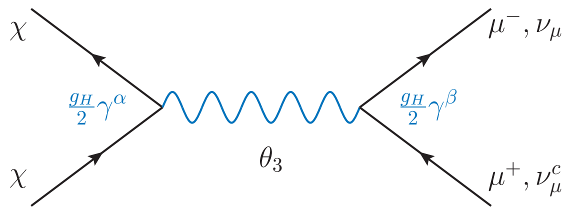

Figure 1. Feynman diagram of dark matter annihilation with corresponding vertex factor.

3.1 Relic density

The dark matter annihilation channels into standard model particles are, $\chi\chi \to \theta_3^* \to \mu^+\mu^-, \nu_\mu^c\nu_\mu$. The annihilation rate of dark matter σv, for a single channel, in the limit of massless leptons, is given by

$$\sigma v = \frac{1}{16\pi} \frac{g_H^4 m_\chi^2}{(s - M_{\theta_3}^2)^2 + \Gamma_{\theta_3}^2 M_{\theta_3}^2} \tag{3.1}$$

where g_H is the horizontal gauge boson coupling, m_χ the dark matter mass, M_{θ_3} and Γ_{θ_3} are the mass and the decay width of $\mathrm{SU(2)_{HV}}$ gauge boson respectively. Since both of the final states (ν_μ, μ) contribute in the relic density, the cross-section of eq. (3.1) is multiplied by a factor of 2 for relic density computation. The contributions to the decay width of θ_3 comes from the decay modes, $\theta_3 \to \mu^+\mu^-, \nu_\mu^c\nu_\mu$. The total decay width is given by,

$$\Gamma_{\theta_3} = \frac{2g_H^2}{48\pi} M_{\theta_3} \tag{3.2}$$

In the non-relativistic limit, $s = 4m_\chi^2(1 + v^2/4)$, then by taking into account the factor of 2, eq. (3.1) simplifies as,

$$\sigma v = \frac{2}{256\pi m_\chi^2} \frac{g_H^4}{(\delta + v^2/4)^2 + \gamma^2} \tag{3.3}$$

where δ and γ are defined as $M_{\theta_3}^2 \equiv 4m_\chi^2(1 - \delta)$, and $\gamma^2 \equiv \Gamma_{\theta_3}^2(1 - \delta)/4m_\chi^2$. If δ and γ are larger than $v^2 \simeq (T/M_\chi)^2$, the usual freeze-out takes place, on the other hand if δ and γ are chosen smaller than v^2 then there is a resonant enhancement of the annihilation CS and a late time freeze-out. We choose $\delta \sim 10^{-3}$ and $\gamma \sim 10^{-4}$, so that we have a resonant annihilation of dark matter. The thermal average of annihilation rate is given as [31–33],

$$\langle \sigma v \rangle (x) = \frac{1}{n_{\mathrm{EQ}}^2} \frac{m_\chi}{64\pi^4 x} \int_{4m_\chi^2}^{\infty} \hat{\sigma}(s) \sqrt{s} K_1\left(\frac{x\sqrt{s}}{m_\chi}\right) ds \tag{3.4}$$

where,

$$n_{\mathrm{EQ}}^2 = \frac{g_i}{2\pi^2} \frac{m_\chi^3}{x} K_2(x) \tag{3.5}$$

$$\hat{\sigma}(s) = 2g_i^2 m_\chi \sqrt{s - 4m_\chi^2}\, \sigma v \tag{3.6}$$

and where $x \equiv m_\chi/T$; $K_1(x)$, $K_2(x)$ represent the modified Bessel functions of second type and g_i is the internal degree of freedom of DM particle. Using eq. (3.3), eq. (3.5) and eq. (3.6) in eq. (3.4), it can be written as,

$$\langle\sigma v\rangle(x) = \frac{g_H^4}{512 m_\chi^2}\frac{x^{3/2}}{\pi^{3/2}}\int_0^\infty \frac{\sqrt{z}\,\mathrm{Exp}[-xz/4]}{(\delta + z/4)^2 + \gamma^2}dz \tag{3.7}$$

where $z \equiv v^2$. We solve the Boltzmann equation for $Y_\chi = n_\chi/s$,

$$\frac{dY_\chi}{dx} = -\frac{\lambda(x)}{x^2}\left(Y_\chi^2(x) - Y_{\chi\mathrm{eq}}^2(x)\right) \tag{3.8}$$

where

$$\lambda(x) \equiv \left(\frac{\pi}{45}\right)^{1/2} m_\chi M_{\mathrm{Pl}}\left(\frac{g_{*s}}{\sqrt{g_*}}\right)\langle\sigma v\rangle(x) \tag{3.9}$$

and where g_* and g_{*s} are the effective degrees of freedom of the energy density and entropy density respectively, with $\langle\sigma v\rangle$ given in eq. (3.7). We can write the $Y_\chi(x_0)$ at the present epoch as,

$$\frac{1}{Y_\chi(x_0)} = \frac{1}{Y_\chi(x_f)} + \int_{x_f}^{x_s} dx\frac{\lambda(x)}{x^2} \tag{3.10}$$

where the freeze-out x_f is obtained by solving $n_\chi(x_f)\langle\sigma v\rangle = H(x_f)$. We find that $x_f \sim 30$ and the relic density of χ is given by,

$$\Omega = \frac{m_\chi s_0 Y_\chi(x_0)}{\rho_c} \tag{3.11}$$

where $s_0 = 2890\,\mathrm{cm}^{-3}$ is the present entropy density and $\rho_c = h^2 1.9\times 10^{-29}\,\mathrm{gm/cm}^3$ is the critical density. We find that by taking $g_H = 0.087$, $\delta \sim 10^{-3}$ and $\gamma \sim 10^{-4}$ in eq. (3.7), we obtain the correct relic density $\Omega h^2 = 0.1199 \pm 0.0027$, consistent with Planck [29] and WMAP [30] data. From g_H and γ we can fix $M_{\theta_3} \simeq 1400\,\mathrm{GeV}$ and $m_\chi \simeq \frac{1}{2}M_{\theta_3} \simeq 700\,\mathrm{GeV}$. There is a large hierarchy between the fourth generation charged fermion mass and the other charged leptons masses. We do not have any theory for the Yukawa couplings and we take the $m_{\mu'}$ mass which fits best the AMS-02 positron spectrum and muon $(g-2)$. A bench mark set of values used in this paper for the masses and couplings is given in table 2.

3.2 Comparison with AMS-02 and PAMELA data

The dark matter in the galaxy annihilates into $\mu^+\mu^-$ and the positron excess seen at AMS-02 [20, 21] appears from the decay of muon. We use publicly available code PPPC4DMID [38, 39] to compute the positron spectrum $\frac{dN_{e^+}}{dE}$ from the decay of μ pairs for 700 GeV dark matter. We then use the GALPROP code [40, 41] for propagation, in which we take the annihilation rate $\sigma v_{\mu^+\mu^-}$, and the positron spectrum $\frac{dN_{e^+}}{dE}$ as an input to the differential injection rate,

$$Q_{e^+}(E,\vec{r}) = \frac{\rho^2}{2m_\chi^2}\langle\sigma v\rangle_{\mu^+\mu^-}\frac{dN_{e^+}}{dE} \tag{3.12}$$

Parameters	Numerical values
g_H	0.087
y_h	0.037
y_A	0.020
$y_{H^\pm}$	0.1
m_χ	700 GeV
$m_{\mu'}$	740 GeV
M_{θ_3}	1400 GeV
M_{θ^+}	1400 GeV
$m_{H^\pm}$	1700 GeV
m_h	125 GeV
m_A	150 GeV
δ	10^{-3}
γ	10^{-4}

Table 2. Bench mark set of values used in the model.

where ρ denotes the density of dark matter in the Milky Way halo, which we take to be the NFW profile [42],

$$\rho_{\rm NFW} = \rho_0 \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}, \qquad \rho_0 = 0.4\,{\rm GeV/cm^3}, \qquad r_s = 20\,{\rm kpc} \tag{3.13}$$

In GALPROP code [40, 41], we take the diffusion coefficient $D_0 = 3.6 \times 10^{28}\,{\rm cm^2\,s^{-1}}$ and Alfven speed $v_A = 15\,{\rm Km\,s^{-1}}$. We choose, $z_h = 4\,{\rm kpc}$ and $r_{\rm max} = 20\,{\rm kpc}$, which are the half-width and maximum size for 2D galactic model respectively. We choose the nucleus spectral index breaks at 9 GeV and spectral index above this is 2.36 and below is 1.82. The normalization flux of electron at 100 GeV is $1.25 \times 10^{-8}\,{\rm cm^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}}$ and for the case of electron, we take breaking point at 4 GeV and its injection spectral index above 4 GeV is $\gamma_1^{\rm el} = 2.44$ and below $\gamma_0^{\rm el} = 1.6$. After solving the propagation equation, GALPROP [40, 41] gives the desired positron flux.

To fit the AMS-02 data, the input annihilation CS required in GALPROP is, $\sigma v_{\chi\chi\to\mu^+\mu^-} = 2.33 \times 10^{-25}\,{\rm cm^3\,s^{-1}}$. The annihilation CS for μ final state from eq. (3.1) is, $\sigma v \approx 2.8 \times 10^{-25}\,{\rm cm^3\,s^{-1}}$, which signifies that there is no extra "astrophysical" boost factor needed to satisfy AMS-02 data. The annihilation rate required for relic density was $\langle\sigma v\rangle \sim 3 \times 10^{-26}\,{\rm cm^3/sec}$ and the factor ~ 10 increase in σv at the present epoch is due to resonant enhancement by taking $m_\chi \simeq \frac{1}{2}M_{\theta_3}$. In figure 2, we plot the output of GALPROP code and compare it with the observed AMS-02 [20, 21] and PAMELA [22] data. We see that our positron spectrum fits the AMS-02 data [20, 21] very well. We also check the photon production from the decay of μ final state by generating the γ-ray spectrum called $\frac{dN_\gamma}{dE}$ from publicly available code PPPC4DMID [38, 39] and propagating it through the GALPROP code [40, 41]. We then compare the output with the observed Fermi-LAT data [43], as shown in figure 3, and find that the γ-ray does not exceed the observed limits.

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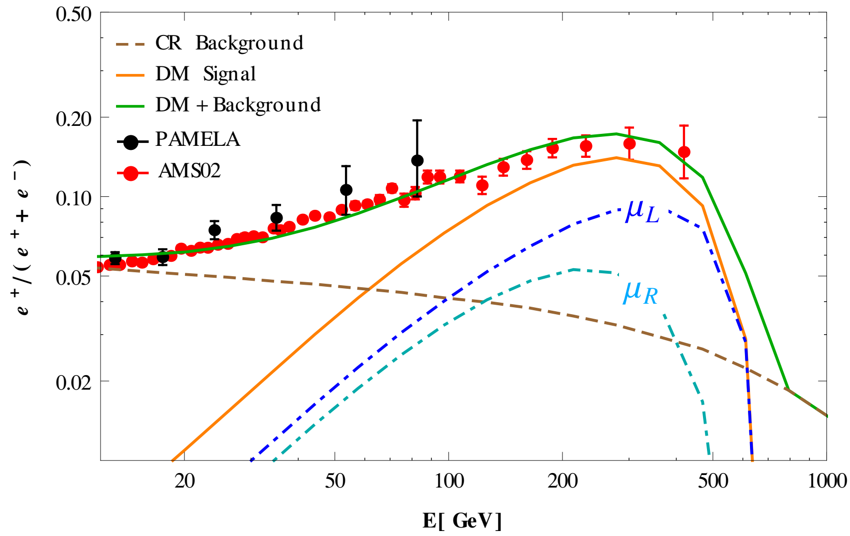

Figure 2. The positron flux spectrum compared with data from AMS-02 [20, 21] and PAMELA [22]. The contributions of different channels (μ_L, μ_R) are shown for comparison.

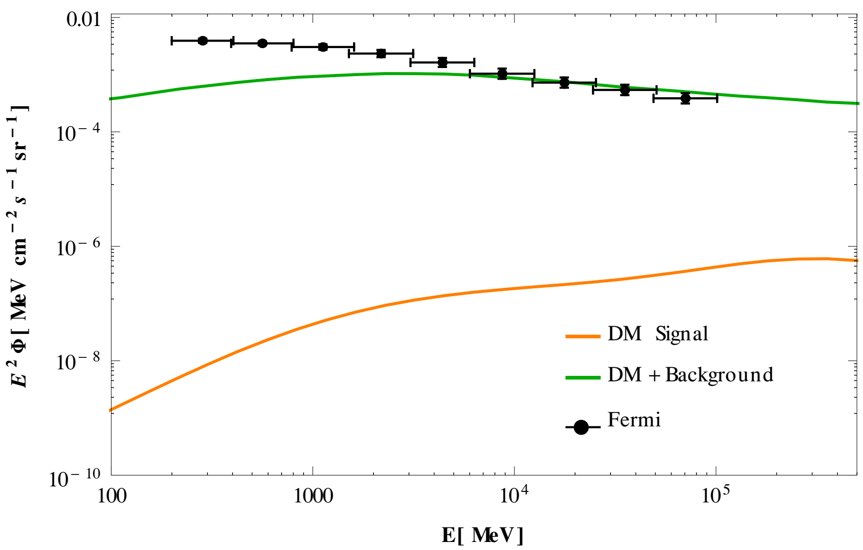

Figure 3. The γ-ray spectrum compared with data from Fermi Lat [43].

There is no annihilation to hadrons, so no excess of antiprotons are predicted, consistent with the PAMELA [25] and AMS-02 [26] data.

4 Muon magnetic moment

The $\mathrm{SU(2)_{HV}}$ horizontal symmetry, which connects muon and 4th generation families, gives extra contributions to muon $(g-2)$. The diagrams that contribute to muon $(g-2)$ with $\mathrm{SU(2)_{HV}}$ charged gauge boson θ^+ and scalar $\eta^\beta_{i\alpha}$ are shown in figure 4.

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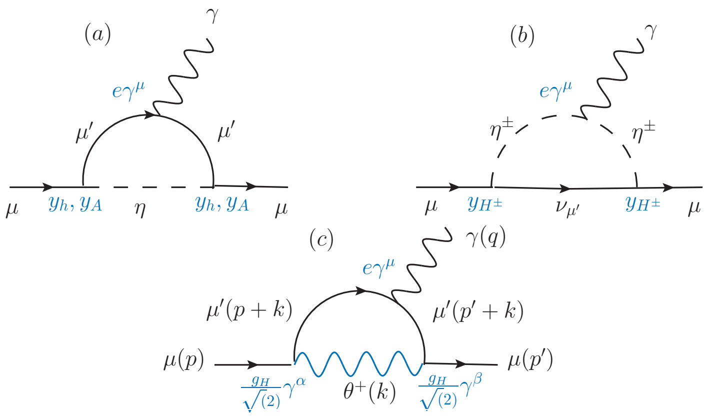

Figure 4. Feynman diagrams of scalar $\eta^\beta_{i\alpha}$ and $SU(2)_{HV}$ gauge boson θ^+, which give contributions to muon $(g-2)$.

We first calculate the contribution from $SU(2)_{HV}$ gauge boson θ^+, which is shown in figure 4(c). For this diagram the vertex factor of the amplitude $\mu(p')\Gamma_\mu\mu(p)\epsilon^\mu$ is,

$$\Gamma_\mu = \frac{eg_H^2}{2}\int \frac{d^4k}{(2\pi)^4}\gamma^\beta \frac{(\not{p}' + \not{k} + m_{\mu'})}{(p'+k)^2 - m^2_{\mu'}}\gamma_\mu \frac{(\not{p} + \not{k} + m_{\mu'})}{(p+k)^2 - m^2_{\mu'}}\gamma^\alpha \frac{g_{\alpha\beta}}{k^2 - M^2_{\theta+}} \tag{4.1}$$

we perform the integration and use the Gorden identity to replace,

$$(p_\mu + p'_\mu) = 2m_\mu\gamma_\mu + i\sigma^{\mu\nu}q_\nu \tag{4.2}$$

and identify the coefficient of the $i\sigma^{\mu\nu}q_\nu$ as the magnetic form factor. The contribution to Δa_μ is,

$$[\Delta a_\mu]_{\theta+} = \frac{m^2_\mu}{16\pi^2}\int_0^1 dx \frac{g_H^2\left(\frac{2m'_\mu}{m_\mu}(x-x^2) - (x-x^3)\right)}{(1-x)m^2_{\mu'} - x(1-x)m^2_\mu + xM^2_{\theta\pm}} \tag{4.3}$$

In the limit of $M^2_{\theta+} \gg m^2_{\mu'}$, we get the anomalous magnetic moment,

$$[\Delta a_\mu]_{\theta+} = \frac{g_H^2}{8\pi^2}\left(\frac{m_\mu m_{\mu'} - 2/3m^2_\mu}{M^2_{\theta+}}\right) \tag{4.4}$$

we note that in eq. (4.4), the first term is dominant which shows $m_\mu m_{\mu'}$ enhancement in the muon $(g-2)$.

In our model, the contribution from the neutral higgs η (CP-even h and CP-odd A) is shown in figure 4(a). The $(g-2)$ contribution of this diagram is [44],

$$\begin{aligned}[\Delta a_\mu]_{h,A} = &\frac{m^2_\mu}{8\pi^2}\int_0^1 dx \frac{y_h^2\left(x^2 - x^3 + \frac{m_{\mu'}}{m_\mu}x^2\right)}{m^2_\mu x^2 + (m^2_{\mu'} - m^2_\mu)x + m^2_h(1-x)} \\ &+ \frac{m^2_\mu}{8\pi^2}\int_0^1 dx \frac{y_A^2\left(x^2 - x^3 - \frac{m_{\mu'}}{m_\mu}x^2\right)}{m^2_\mu x^2 + (m^2_{\mu'} - m^2_\mu)x + m^2_A(1-x)}\end{aligned} \tag{4.5}$$

where y_h, y_A represent the Yukawa couplings of neutral CP-even and odd higgs respectively and their masses are denoted by m_h and m_A respectively. We shall calculate the contributions from the lightest scalars only, which give the larger contributions in compare to heavy scalars. In the limits $m_{\mu'}^2 \gg m_h^2$, $m_{\mu'}^2 \gg m_A^2$, doing the integration in eq. (4.5) we get the anomalous magnetic moment,

$$[\Delta a_\mu]_{h,A} = \frac{1}{8\pi^2}\left(\frac{3m_\mu m_{\mu'}(y_h^2 - y_A^2) + m_\mu^2(y_h^2 + y_A^2)}{6m_{\mu'}^2}\right) \tag{4.6}$$

In a similar way, the contribution from the mass eigenstate $H^\pm$ of charged higgs $\eta^\pm$, shown in figure 4(b), is given by [44],

$$[\Delta a_\mu]_{H^\pm} = \frac{m_\mu^2}{8\pi^2}\int_0^1 dx \frac{y_{H^\pm}^2\left(x^3 - x^2 + \frac{m_{\nu_{\mu'}}}{m_\mu}(x^2 - x)\right)}{m_\mu^2 x^2 + (m_{H^\pm}^2 - m_\mu^2)x + m_{\nu_{\mu'}}^2(1-x)} \tag{4.7}$$

where $y_{H^\pm}$ and $m_{H^\pm}$ are the Yukawa coupling and mass of the charged higgs respectively. We perform the integration (eq. (4.7)) in the limit $m_{H^\pm}^2 \gg m_{\nu_{\mu'}}^2$, and get the anomalous magnetic moment,

$$[\Delta a_\mu]_{H^\pm} = -\frac{y_{H^\pm}^2}{8\pi^2}\left(\frac{3m_\mu m_{\nu_{\mu'}} + m_\mu^2}{6m_{H^\pm}^2}\right) \tag{4.8}$$

So the complete contribution to muon $(g-2)$ in our model is given as,

$$\Delta a_\mu = [\Delta a_\mu]_{\theta^+} + [\Delta a_\mu]_{h,A} + [\Delta a_\mu]_{H^\pm} \tag{4.9}$$

As discussed before, in our model the lightest CP-even scalar h_1 is mainly composed of η, so we can write,

$$y_h \sim k_2 \cos\alpha_1 \tag{4.10}$$

where α_1 is the mixing angle between CP-even mass eigenstate h_1 and gauge eigenstate η, and k_2 is the Yukawa coupling defined in eq. (2.8). In the similar way, we assume that lightest pseudoscalar A and charged higgs $H^\pm$ are also mainly composed of η, so that we can write

$$y_A \sim k_2 \cos\alpha_2\,, \qquad y_{H^\pm} \sim \tilde{k}_2 \cos\alpha_3 \tag{4.11}$$

where α_2 is the mixing angle between CP-odd scalars and α_3 is the mixing angle between the charged scalars. $\tilde{k}_2$ denotes the Yukawa coupling defined in eq. (2.8).

In the $SU(2)_H$ gauge boson sector, we take $g_H = 0.087$, $M_{\theta^+} \approx 1400\,\text{GeV}$ ($M_{\theta_3} \approx M_{\theta^+}$), which are fixed from the requirement of correct relic density and we take $m_{\mu'} = 740\,\text{GeV}$, coming from the stability requirement of dark matter ($m_{\mu'} > m_\chi$). After doing numerical calculation, we get $[\Delta a]_{\theta^+} = 3.61 \times 10^{-9}$.

The contribution from (h, A) scalars depend on the parameter $k_2^2(\cos^2\alpha_1 - \cos^2\alpha_2)$, which we assume to be $\simeq 10^{-3}$ and obtain $[\Delta a_\mu]_{h,A} = 0.82 \times 10^{-9}$. For the charged scalar contribution, we assume $\tilde{k}_2 \cos\alpha_3 = 0.1$ and $m_{H^\pm} = 1700\,\text{GeV}$ and obtain $[\Delta a_\mu]_{H^\pm} = -1.53 \times 10^{-9}$. Adding the contributions from θ^+, (h, A) and $H^\pm$, we get

$$\Delta a_\mu = 2.9 \times 10^{-9} \tag{4.12}$$

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which is in agreement with the experimental result [1, 2] within 1σ. To get the desired value of muon $(g-2)$, we have to consider a large hierarchy between the neutral higgs ($m_h \sim 125\,\mathrm{GeV}$, $m_A \sim 150\,\mathrm{GeV}$) and the charged higgs $m_{H^\pm} \sim 1700\,\mathrm{GeV}$. These masses have to arise by appropriate choices of the couplings in the higgs potential of $(\phi_i,\ \eta^\beta_{i\alpha},\ \chi_\alpha)$.

5 Result and discussion

We studied a 4th generation extension of the standard model, where the 4th generation leptons interact with the muon family via $\mathrm{SU(2)_{HV}}$ gauge bosons. The 4th generation right-handed neutrino is identified as the dark matter. We proposed a common explanation to the excess of positron seen at AMS-02 [20, 21] and the discrepancy between SM prediction [3–9] and BNL measurement [1, 2] of muon $(g-2)$. The $\mathrm{SU(2)_{HV}}$ gauge boson θ^+ with 4th generation charged lepton μ' and charged higgs $H^\pm$, give the required contribution to muon $(g-2)$ to satisfy the BNL measurement [1, 2] within 1σ. The LHC constraints on 4th generation quarks is evaded by extending the higgs sector as in [35, 36]. In our horizontal $\mathrm{SU(2)_{HV}}$ gauge symmetry model, we also explain the preferential annihilation of dark matter to $\mu^+\mu^-$ channel over other leptons and predict that there is no antiproton excess, in agreement with PAMELA [25] and AMS-02 [26] data. Since the dark matter has gauge interactions only with the muon family at tree level, we can evade the bounds from direct detection experiments [45, 46] based on scattering of dark matter with the first generation quarks.

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